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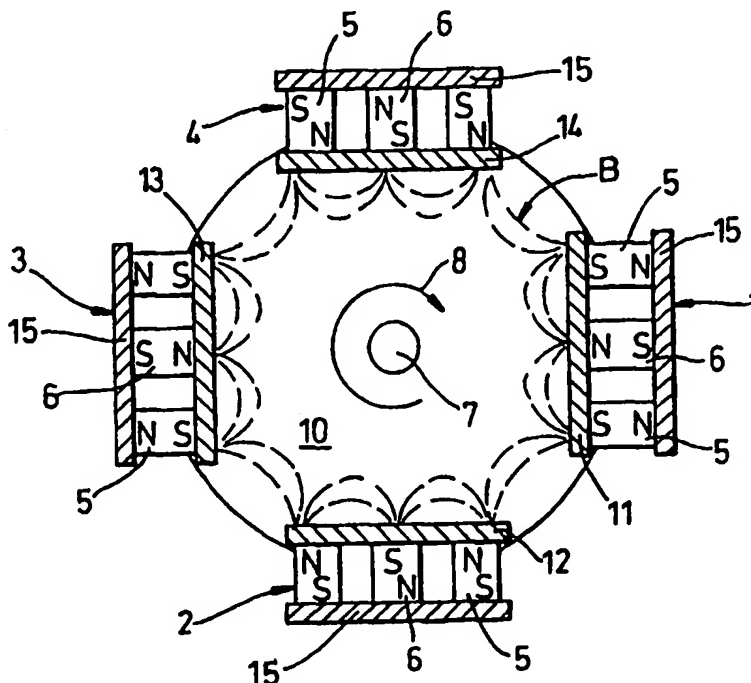
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(54) Title: METHOD AND CUTTING TOOL FOR CUTTING OF WORKPIECES

## (57) Abstract

A method of cutting a workpiece is disclosed in which the workpiece is cut with a cutting surface of a cutting tool coated with a carbon based solid lubricant coating and in which during cutting, the cutting tool is lubricated and/or cooled with an aqueous coolant which may be oil-free. Also disclosed is a cutting tool having a cutting surface which is coated with a carbon based coating wherein carbon-carbon bonding within the coating is mostly of the graphitic sp<sup>2</sup> form.



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## METHOD AND CUTTING TOOL FOR CUTTING OF WORKPIECES

This invention relates to the cutting of workpieces. The term "cutting" is used herein in a broad sense, and operations embraced by that term include: sawing, drilling, milling, planing, thread-cutting, reaming and turning. Workpieces which may be "cut" in any of those senses include  
5 articles made (or being made) from metals, including alloys, reinforced composite materials, glass, ceramics, plastics, wood and wood products.

The invention has particular reference to lubricated cutting, especially the cutting of metals, and it will hereinafter be described with particular reference to that. In industry metals are subjected to various machining  
10 operations including turning, cutting, drilling and milling. Typically these operations are carried out under oil lubrication. The oil may be simply oil of one grade or another, or it may be in an emulsion with water. These lubricants are usually expensive, they can cause health hazards to the machine operator, and there are environmental problems  
15 associated with their disposal.

A further problem associated with the use of conventional liquid lubricants is that there is a tendency to use increasingly high speeds during machining in order to improve productivity. It is doubtful that the liquid lubricants currently used are effective because they will not be able  
20 to penetrate to the actual cutting zone at such high speeds. This leads to unlubricated cutting, an increase in the cutting forces, and consequently results in the generation of significant quantities of heat. Overheating of the cutting tool promotes wear.

Various methods have been proposed in order to alleviate these problems.

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Firstly, the lubricant can be introduced in small quantities for example by spraying. While this reduces the amount of lubricant used and accordingly reduces the environmental problems associated with the disposal of waste lubricant, it will have a reduced cooling effect and it  
5 will not solve the problems presented by high machining speeds.

Hard and heat resistant coatings such as titanium aluminium nitride coatings have been used successfully. It will be appreciated, however, that the use of such coatings mitigates the disadvantages referred to above rather than solving the problem. Such coatings are not lubricants and  
10 they accordingly do not reduce the cutting forces involved.

It has also been proposed to dispense entirely with liquid lubricants. This has been done by using solid lubricant coatings based for example on molybdenum disulphide. Tools bearing such coatings are increasingly being used for dry machining and in fact they probably offer the best  
15 solution to the problem which has been presented to date.

While some molybdenum disulphide coatings can withstand wet conditions, the wear resistance of many molybdenum disulphide coatings regrettably tends to decrease if the coating is wet and this precludes the use of a liquid lubricant/coolant with such coatings.

20 It is an object of this invention to provide a new and improved method of cutting workpieces.

According to the present invention there is provided a method of cutting a workpiece in which the workpiece is cut with a cutting surface of a cutting tool coated with a carbon based solid lubricant coating and  
25 wherein during cutting, the cutting tool is lubricated and/or cooled with an aqueous coolant.

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The invention extends to a cutting tool having a cutting surface which is coated with a carbon based coating.

Carbon based coatings can have excellent dry lubrication properties and can be used in the same way as molybdenum disulphide based coatings for  
5 dry machining.

It is, however, to be noted that the performance of molybdenum disulphide can sometimes be very poor under water. Perhaps surprisingly, in distinction to this, the performance of carbon based coatings can be considerably enhanced by the presence of water. The  
10 coefficient of friction of the coating can be reduced to about one half of its dry value, and the wear can be reduced by a factor of at least ten.

The coolant is preferably oil free and it may be water.

Just as with the conventional lubricant or coolant it is doubtful whether water can be effective in lubricating the cutting point at the highest  
15 cutting speeds which are now used or envisaged, but even if the water cannot penetrate to the cutting point, the carbon based coating envisaged has a low intrinsic coefficient of friction, and the water is still helpful in providing efficient cooling of the tool thus allowing even higher cutting speeds.

20 Water is cheap and its use presents no particular health problems and no problems in disposal. Ordinary tap water may be used.

A method according to the invention presents particular advantages when the cutting operation is a machining operation. and when it is applied to the cutting of a metal workpiece or a reinforced composite workpiece.

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The carbon based coating may be a hydrogenated Me:C coating or a diamond-like coating. These coatings provide good lubrication properties under water. It is preferred however, that carbon-carbon bonding within the coating is mostly of the graphitic sp<sup>2</sup> form. Such a graphitic coating  
5 can have a low coefficient of friction, a lower wear rate and a higher load bearing capacity than either a diamond-like carbon coating or a hydrogenated Me:C coating.

In some preferred embodiments of the invention, the cutting tool has a composite coating which comprises a first hard layer of a nitride, carbide,  
10 carbo-nitride or boride followed by a said carbon-based coating layer.

In some preferred embodiments of the invention the cutting tool is coated with a plurality of coating layers of which an uppermost is a carbon-based coating.

The cutting tool may be formed from a steel or a tungsten carbide based  
15 material. Other materials may also be used and in some preferred embodiments of the invention the cutting tool is constructed from a ceramic material.

The cutting tool may be constructed from a combination of steel, tungsten carbide based material and ceramic.

20 The aqueous coolant may be supplied to the cutting zone by any appropriate method for example as a flood lubricant or a spray lubricant or through holes or apertures within the cutting tool.

Advantageously the carbon based coating is a coating formed in accordance with International Patent Application No: WO99/27893, and

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the full contents of that specification are incorporated herein by this reference.

It is rather surprising that a carbon-based coating which is graphitic in structure can in fact have tribological properties, such as greater hardness and wear-resistance, which are much improved over the properties of a carbon-containing coating which is of diamond-like structure.

Such a graphitic coating is preferably formed by sputtering, suitably by a method which comprises using a sputter ion plating system with at least one carbon target in which an ion current density of above  $0.5\text{mA}/\text{cm}^2$  is applied at the cutting tool to be coated in order to deposit a carbon coating layer.

This method provides a coating of much improved quality, in particular as regards its tribological properties. The coating layer contains sufficient carbon for there to be carbon-carbon (as opposed to carbide) bonds within it. When deposited in this way, it will be found that those carbon-carbon bonds are predominantly of the  $\text{sp}^2$  or graphitic type.

In some preferred embodiments of the invention, the carbon-based coating comprises a succession of carbon and metal-containing layers and in which carbon-carbon bonding within the or each carbon layer is mostly of the graphitic  $\text{sp}^2$  form, and the invention includes a method of applying a carbon coating to a cutting tool comprising by sputter ion plating with at least one carbon target and at least one metal target in order to deposit a carbon coating layer and a metal-containing coating layer.

The use of targets of different compositions, particularly when the cutting tool is suitably rotated, allows a considerable degree of control of the final coating composition and of different strata within it.

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We have found that the presence of a said metal-containing layer can make a significant contribution to the coating properties. In some preferred embodiments of the invention, such a metal-containing layer is an underlayer deposited directly onto the cutting tool to be overcoated  
5 with carbon. Such a metal-containing underlayer is very effective in promoting adhesion between a carbon layer and a cutting tool.

Thus a method according to the invention preferably comprises using a metal target to form a metal-containing underlayer directly onto the cutting tool which is over-coated with the or a said carbon coating layer.

10 Such a metal-containing underlayer is preferably deposited to a thickness of between 50 and 200 nm.

The underlayer can comprise an initial stratum of metal followed by a second stratum consisting of the metal and carbon produced by co-deposition from metal and carbon targets. This stratum may be harder  
15 than the metal stratum and can improve the tribological behaviour of the subsequent carbon coating.

Alternatively, or in addition, there may be provided a one or more metal-containing layers each of which is an intermediate layer located between successive carbon layers. This promotes cohesiveness of the coating as a  
20 whole. We have found that when a uniform (graphitic) carbon coating is deposited on a cutting tool, once a certain thickness threshold is exceeded, the coating may have a tendency to spall and that this tendency increases with increasing thickness. We have also found, however, that this tendency is alleviated or even eliminated if thin carbon layers are  
25 interleaved with metal-containing layers. In order to avoid any risk of such spalling, a said carbon-containing layer is preferably formed to a thickness of up to 1  $\mu$ m.



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Significant advantages are given by embodiments of the invention in which said coating is built up from a succession of alternating metal-containing and carbon coating layers respectively formed predominantly (that is, more than 50 atoms %) from metal and from carbon. By making  
5 use of this feature, the coating as a whole may be built up to any desired thickness, for example up to 10  $\mu\text{m}$ , preferably in the range 1 to 5  $\mu\text{m}$ , and without risk of spalling of the carbon, provided that the carbon layers have thicknesses below 1  $\mu\text{m}$ .

The use of a transition metal, that is a metal in one of Groups 3 to 10  
10 (new IUPAC notation) of the Periodic Table as shown on page 1-15 of Handbook of Chemistry and Physics, 77th Edition 1996-1997 (CRC Press), preferably chromium or titanium, is found particularly effective.

A said coating is suitably formed by magnetron sputter ion plating, and most preferably by a technique known as closed field unbalanced  
15 magnetron sputter ion plating (CFUBMSIP). Such a technique can be used to produce coatings in accordance with this invention which have quite outstanding properties. Apparatus for use in such a technique is described later in this specification with reference to the accompanying diagrammatic drawing. Such apparatus is further described in UK Patent  
20 No. 2 258 343 (and corresponding European Patent No 0 521 045 and US Patent No 5,556,519), and the full contents of that specification are incorporated herein by this reference.

Such a CFUBMSIP method of deposition is the preferred method of deposition although other methods giving high ion current density can also  
25 be used.

When sputter ion plating, the cutting tool being coated is preferably held at a bias voltage of from floating voltage to 250V negative. These are

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inclusive values, and the bias voltage applied may be DC, pulsed DC or RF. Preferably such bias is between 50V and 150V negative, and the best results have been attained when such bias is between 70 and 100 volts negative.

- 5 A very simple and preferred way of forming a said coating is to rotate the cutting tool while it is being coated. This assists in achieving an even coating on the cutting tool, and also has advantages in the deposition of a plural layer coating.

- 10 A particularly convenient way of achieving the optimum proportions of carbon and metal in a multi-layer coating is to use three carbon-donating targets and one metal-donating target for forming the coating. The cutting tools may be rotated in a working space between such targets and this is a highly advantageous way of building up a coating from a succession of alternating metal-containing and carbon strata.

- 15 The rotational speed of the cutting tool and the rates of deposition of the carbon and metal are suitably so controlled as to yield a period of at least 3 nm in the coating strata. If the period is too small, there is a risk that the carbon and metal will react and combine to form a metal carbide. While metal carbide may be tolerated in any said metal-containing layer,
- 20 the replacement of carbon-carbon bonds by metal carbide bonds in a said carbon layer would detract from the quite remarkable properties afforded by this invention. It may be noted that it is the carbon layers having graphitic carbon-carbon bonds which provide these tribological properties; while such carbon layers may contain small proportions of metal (and
- 25 indeed this may be difficult to avoid when using some deposition techniques) the presence of such metal is purely incidental, and the excellent wear-resistance and low friction properties do not depend on the

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carbon layers containing any metal. The metal-containing layers have a strengthening or adhesion promoting or anti-spalling effect, and they thus allow the coating to be built up to a greater thickness if this is desired. The incorporation of metal layers can also enable the coating to withstand  
5 higher loads.

Preferably, said coating is deposited under an atmosphere containing a noble gas. The use of a noble gas avoids contamination of the deposited coating by compounds of a chemically active gas. It is generally found most convenient to use argon. The argon gas pressure in the sputter  
10 system is not critical and can be between about  $7 \times 10^{-2}$  Pa ( $5 \times 10^{-4}$  torr) and about 1 Pa ( $1 \times 10^{-2}$  torr). Preferably, said coating is deposited under an argon-containing atmosphere at a pressure of from 0.07 Pa to 0.6 Pa.

While it is desirable to avoid contamination of the coating by compounds of a chemically active gas, the invention does not exclude the possibility  
15 of deliberately modifying the coating composition by introducing such a gas into the atmosphere in the sputtering chamber.

Thus for example, the coatings which are formed can be modified by the inclusion of a hydro-carbon gas in the sputtering atmosphere during deposition as is provided in some embodiments of this invention. A  
20 feature of such a method may be that a mixture of carbon and metal is sputtered to deposit as a metal-containing layer on the cutting tool (the article being coated) which layer also contains additional carbon produced by breakdown of any hydrocarbon gas present in the working atmosphere and which deposits directly on the electrically biased cutting tool.  
25 Deposition of a said carbon layer may be by a combination of sputtering from the carbon target and breakdown of the hydrocarbon gas in the plasma.

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Also, the coatings as described above can be modified by the addition of nitrogen to the working atmosphere during deposition. This can result in coatings modified by reaction of the nitrogen with the metal to form metal nitrides or with the carbon to form carbon-nitrogen compounds.

- 5 Such magnetron sputter ion plating apparatus preferably comprises at least two magnetrons adapted to generate a magnetic field between them with field lines extending from one said magnetron to the or an other said magnetron, whereby said magnetrons, and field lines extending directly from one said magnetron to the or an other, form a barrier which tends to  
10 prevent the escape of electrons from within a plasma-containing working space within which a cutting tool may be coated.

Preferably the arrangement is such as to permit the achievement of an ion current density of at least  $0.5\text{mA}/\text{cm}^2$ .

- 15 The use of carbon and metal targets allows great flexibility in the choice of conditions under which the coating layers are deposited. For example such conditions may be varied to vary the composition of a said metal-containing underlayer as it is deposited, for example so that its composition varies from metal, adjacent the cutting tool surface, through metal carbide to (graphitic) carbon at the carbon layer.

- 20 The invention extends to:

- a tool bearing a carbon-containing coating, wherein said coating has a specific wear rate under wet conditions of less than  $10^{-16} \text{ m}^3/\text{Nm}$ , and preferably less than  $10^{-17} \text{ m}^3/\text{Nm}$ ;
- a tool bearing a carbon-containing coating, wherein said coating has  
25 an adhesion critical load of at least 70N;

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- a tool bearing a carbon-containing coating, wherein said coating has a hardness of at least 1000 VHN;
  - a tool bearing a carbon-containing coating, wherein said coating has a coefficient of friction (dry) of not more than 0.1;
- 5 A said carbon-containing layer should most preferably have a structure with one or more of the following properties:
- an absence of crystallinity detectable by X-ray diffraction or by selected area diffraction in a transmission electron microscope;
  - a predominant carbon-carbon bonding within the layer of the sp<sup>2</sup> form indicated by Raman spectroscopy;
  - predominantly graphitic (sp<sup>2</sup>) bonding with very small grain size;
- 10

The very high hardness which may be exhibited by the coatings indicates that there must be some cross bonding. The coating structure may contain some C<sub>60</sub>, and some sp<sup>3</sup> bonding may be present.

- 15 We have made various references to the excellent wear resistance properties afforded by coatings formed in accordance with this invention. It will be appreciated that different methods of measuring wear resistance may give different results, and accordingly, references in this specification, including its claims, to wear resistance of a given coating
- 20 are, unless otherwise specified, references to specific wear resistance measured by the following test

#### SPECIFIC WEAR RESISTANCE TEST.

- A test coating is formed under the same conditions as the given coating but on a substrate which consists of a flat high-speed steel disc. The wear
- 25 resistance of the test coating is measured in the following way.

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A tungsten carbide pin having a hemispherical head which is uncoated and has a radius of 2.5 mm is rubbed against the test coating on the flat high speed steel disc. The specific loading on the pin is between 20 and 100 N, and the disc is rotated to give a rubbing speed of 180 mm per minute.

- 5 (We have found that provided the loading on the pin is between 20 and 100 N, the specific wear rate afforded by this test is substantially independent of the actual loading.) When wet conditions are specified, the rubbing is performed under water unless another liquid is specified.

- 10 A taper section (angle less than 5°) through the rubbed surface is examined using an optical microscope at a magnification of 500× to measure of the wear of the coating. This method easily enables the measurement of specific wear rates as low as  $10^{-17} \text{ m}^3/\text{Nm}$ .

- 15 It will be appreciated that other tests are possible, and indeed some other tests are referred to in this specification. It is the test of the immediately preceding paragraphs which is the one which governs the values given in the claims of this specification.

- 20 A coating formed in accordance with this invention is useful in providing a hard, low friction, wear resistant surface for use in conditions where components are highly loaded, whether unlubricated or lubricated by oil or an aqueous medium. Examples of components which could usefully be provided with a coating in accordance with this invention abound in the metal-working industries. Drill bits, saw blades, thread-cutting taps and dies, milling cutters, and lathe tools may be mentioned.

- 25 This invention enables the provision of a new, hard-wearing, low-friction, cutting tool.

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Preferred embodiments of the invention will now be described by way of Example and with reference to the accompanying diagrammatic drawing which shows a plan view of a closed field unbalanced magnetron sputter ion plating system.

- 5 In the drawing, four magnetrons 1, 2, 3, and 4 each have an outer ring magnet 5 and a central core magnet 6. The magnetrons are arranged around a carrier 7 for cutting tools which are to be coated. The cutting tool carrier 7 is arranged to rotate as indicated by arrow 8 about an axis. It is usually most convenient to arrange for the cutting tool carrier 7 to rotate about a substantially vertical axis. In the drawing, which illustrates a practical arrangement, the outer magnets 5 of the magnetrons 1 and 3 are of south polarity and their inner core magnets 6 are of north polarity (in their regions which face the cutting tool carrier 7). The outer magnets 5 of magnetrons 2 and 4 are of north polarity and their cores 6 of south polarity (again, in their regions facing the cutting tool carrier 7). Thus the magnetic field lines B of magnetrons 1, 2, 3, and 4 form a continuous barrier, trapping electrons which diffuse from the magnetron plasmas, and they at least in part define a working space 10 within which the cutting tool carrier 7 rotates during the coating process. That barrier may extend over the axial ends of the working space 10 (usually its top and bottom) or not, as desired.

The drawing also shows targets 11, 12, 13, 14 of source material associated with the respective magnetrons 1, 2, 3, and 4. These targets cover the faces of the magnetron poles facing the cutting tool carrier 7, and the magnetrons each have a soft iron backing plate 15 to complete their internal magnetic circuits.

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As will be seen from the drawing, the magnetic field lines B surround the cutting tool carrier 7 and serve to form a tubular working space 10 within which electrons are trapped. Since the electrons cannot escape the system, except perhaps at its axial ends, they are available to enhance the ionisation associated with the cutting tool, creating a high ion density.

In use, an inert gas such as argon is provided in the chamber of the system and electrons are accelerated in the chamber by a potential difference applied to the magnetron targets 11, 12, 13, 14 to ionize the gas, producing more electrons and argon ions. The argon ions present in the chamber bombard the targets of source material and produce a coating flux of source material. It is suitable for three of the targets to be of carbon while one is of a transition metal such as chromium or titanium. The argon ions also bombard the cutting tool. The magnetic field lines B serve to form a continuous barrier to the electrons diffusing from the magnetron discharges and ensure that these electrons are not lost to the system through its sides without performing their useful function of enhancing the glow discharge associated with the negatively electrically biased cutting tools, increasing the ion current to the cutting tool.

The magnetrons 1, 2, 3, 4 are provided approximately equi-angularly spaced in a ring with the cutting tool carrier 7 at its centre. They are carried within a coating chamber (not shown) which may be of cylindrical shape having axial bearings for supporting the cutting tool carrier 7 at its top and base. A pumping port (not shown) is provided out of line with the four magnetrons, for example in its base.

The magnetic field B forms a continuous ring surrounding the cutting tool and traps electrons in the ring. Since an even number of magnetron pole assemblies is provided the flux ring can be complete. There is an



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advantage in providing an even number of magnetrons. Six or eight magnetron pole assemblies are also considered good configurations, but clearly more could be provided if desired, and a system with but two magnetrons could also be used. Adjacent magnetrons would have outer magnet assemblies of opposite polarity, as illustrated.

In the arrangement shown in the drawing, the plating system is arranged with three carbon-donating targets and one chromium-donating target, and the cutting tools to be coated are held on a rotating carrier 7 mounted between the targets to promote uniformity of coating and so that a multi-layer coating results.

In order to obtain stress-free coatings we prefer to use a fairly low bias voltage on the cutting tool to be, and accordingly the cutting tools are maintained at a bias voltage of 70V negative. The sputtering chamber contains an argon atmosphere at a pressure of about 0.3 Pa ( $2 \times 10^{-3}$  torr).

Use of the four-target closed field unbalanced magnetron sputter ion plating system ensures an ion current density at the cutting tool which is in excess of  $0.5 \text{ mA/cm}^2$ . At low ion current densities, typically less than  $0.5 \text{ mA/cm}^2$ , the coating has been found to have inferior tribological properties.

The power applied to the carbon target of the magnetron source is not critical and is limited only in the fact that high powers cause cracking of the target.

A typical deposition sequence which produces coatings with quite exceptional tribological properties is as follows:-

- i. Ion clean the items to be coated;
- ii. deposit 0.05 to  $0.2 \mu\text{m}$  of metal;

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- iii. co-deposit metal and carbon to produce an underlayer stratum of chromium carbide of between 0.1 and 0.3 $\mu$ m thickness;
- iv. gradually reduce the power on the metal target while rotating the cutting tool to produce a multi-stratum coating layer consisting of successive carbon and metal-containing strata.

This final coating can be as thick as the particular application demands but is typically between 1 and 5 $\mu$ m.

The carbon or carbon/metal multi-layer coatings deposited as described above have been found to have remarkable tribological properties, with an Adhesion Critical Load > 70N.

The Vickers hardness of the coating formed under the conditions specified was about 2500 VHN, but this can be varied from 1000 to more than 3000 VHN depending on the exact deposition conditions.

Coefficient of friction about 0.08 dry and about 0.04 wet.

- 15 The specific wear rate for unlubricated (dry) rubbing in normal (humid) atmosphere is surprisingly low at about  $2 \times 10^{-17} \text{m}^3/\text{Nm}$ . Under lubricated (wet) rubbing, the wear rate is much lower and it was in fact so low that it was difficult to make an accurate measurement of the wear rate under water lubrication. This implies that such wear rate may be below
- 20  $10^{-18} \text{m}^3/\text{Nm}$  and possibly even below  $10^{-19} \text{m}^3/\text{Nm}$ .

The coating has the ability to resist wear at very high loads: loads of up to 800 N/mm<sup>2</sup> can be sustained by carbon layers and up to 3000 N/mm<sup>2</sup> can be sustained by multi-layer coatings in accordance with the most preferred embodiments of this invention. (Load measured when the coating was deposited on a cutting tool of high speed steel.) The wear

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coefficient quoted above for unlubricated rubbing is obtained at specific loads over  $1800 \text{ N/mm}^2$ .

It may be noted here that coatings formed as described are not intended for use in a vacuum. We have conducted tests under high vacuum and in  
5 a dry nitrogen atmosphere, and we have found that the wear rate in high vacuum or dry atmospheres is higher. This is consistent with a carbon coating layer having a largely graphitic structure.

Little  $\text{sp}^3$  bonding, i.e. diamond bonding, has been detected by UV Raman spectroscopy, and Raman spectroscopy indicates that the bonding  
10 is largely  $\text{sp}^2$ , i.e. graphitic bonding. This is consistent with the fact that the coating is electrically conducting and with the higher wear rate experienced under high vacuum conditions.

The hardness between 1000 and 3000 VHN is exceptional for graphitic carbon. The deposition conditions provided by the CFUBMSIP (or other  
15 high icd systems) must produce some form of cross bonding to cause the high hardness.

The combination of high hardness and low friction is presumably responsible for the exceptionally low wear rate which has been shown in many tests and which is found to be consistently much lower than other  
20 carbon based coatings such as metal-containing, diamond-like carbon coatings, and the load-bearing capacity of our new carbon coatings is also much higher.

Coatings formed as described above are of particular value in the field of cutting generally, and especially in the field of metal machining because  
25 the resulting coatings have remarkable tribological properties; they are stable in water-based fluids and have very, very, low wear rates when

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wetted by those fluids. Our tests have shown that the wear rate of the coating under unlubricated (dry) rubbing conditions is very low (specific wear rate about  $10^{-17} \text{ m}^3/\text{Nm}$  as mentioned above), but when rubbed under water, the wear rate is so low as to make quantitative measurement very  
5 difficult. These tests were performed at low rubbing speeds, where hydrodynamic effects were impossible, and the low wear rate is truly a property of the coating.

A composite coating was deposited onto various tools by the method as described above by subjecting the tools to sputter ion plating. The tools  
10 in question were respectively: drill bits, lathe tools, milling bits, plane blades, reamers, thread cutting taps and dies, and saw blades.

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**CLAIMS**

1. A method of cutting a workpiece in which the workpiece is cut with a cutting surface of a cutting tool coated with a carbon based solid lubricant coating and wherein during cutting, the cutting tool is lubricated and/or cooled with an aqueous coolant.
- 5 2. A method according to Claim 1, wherein the coolant is substantially oil-free.
3. A method according to Claim 2, wherein the coolant is water.
4. A method according to any preceding claim, wherein the cutting operation is a machining operation.
- 10 5. A method according to any preceding claim, wherein the workpiece is a metal workpiece.
6. A method according to of Claims 1 to 4, wherein the workpiece is a reinforced composite workpiece.
7. A method according to any preceding claim, wherein carbon-carbon  
15 bonding within the coating is mostly of the graphitic sp<sup>2</sup> form.
8. A cutting tool having a cutting surface which is coated with a carbon based coating wherein carbon-carbon bonding within the coating is mostly of the graphitic sp<sup>2</sup> form.
9. The invention of any preceding claim, wherein the cutting tool is  
20 coated with a composite coating which comprises a first hard layer of a nitride, carbide, carbo-nitride or boride followed by a said carbon based coating layer.

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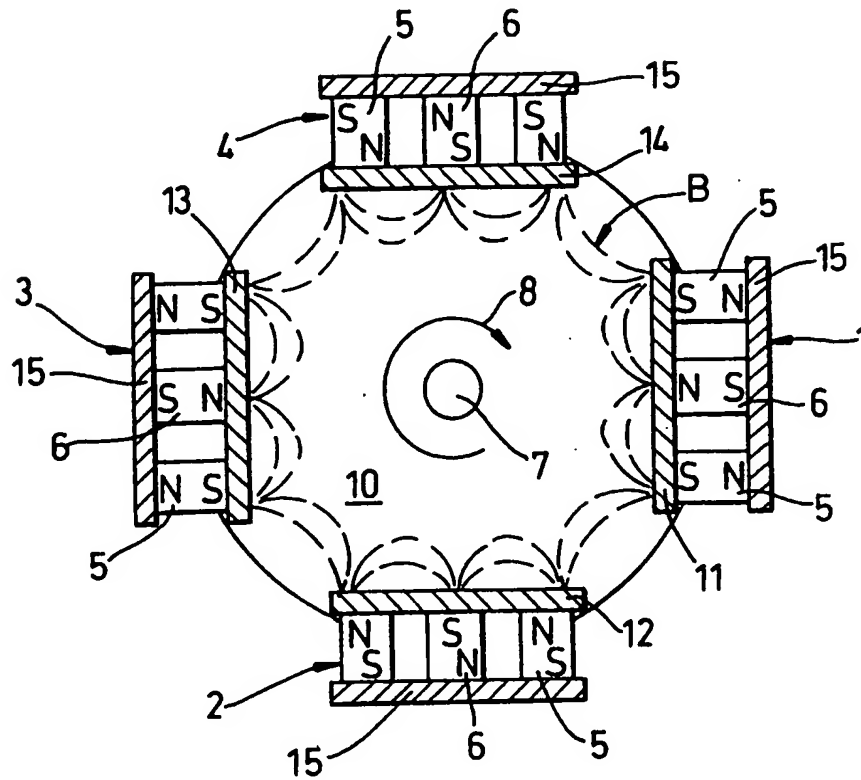
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10. The invention of any preceding claim, wherein the cutting tool is coated with a plurality of coating layers of which an uppermost is a carbon based coating.
11. The invention of any preceding claim, wherein the cutting tool is  
5 formed from a steel.
12. The invention of any preceding claim, wherein the cutting tool is formed from a tungsten carbide based material.
13. The invention of any preceding claim, wherein the cutting tool is constructed from a ceramic material.
- 10 14. The invention of any preceding claim, wherein the cutting tool is constructed from a combination of steel, tungsten carbide based material and ceramic.
- 15 15. The invention of any preceding claim, wherein the aqueous coolant is supplied to the cutting zone as a flood lubricant, or a spray lubricant,  
15 or through holes or apertures within the cutting tool.

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## INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER		Interr. nat Application No PCT/GB 00/00855
IPC 7 C23C14/32 C23C14/06 B23B27/14 B23D61/18 B23P15/28 C23C16/26		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) IPC 7 C23C B23B B23D B23P		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practical, search terms used)		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P, X	GB 2 331 998 A (TEER COATINGS LTD) 9 June 1999 (1999-06-09) the whole document	8-14
X	EP 0 480 394 A (SUMITOMO ELECTRIC INDUSTRIES) 15 April 1992 (1992-04-15) the whole document	1-15
X	EP 0 796 930 A (SAACKE ZORN WALZTECH) 24 September 1997 (1997-09-24) the whole document	1-15
X	US 5 786 038 A (LEMELSON JEROME H ET AL) 28 July 1998 (1998-07-28) column 2, line 57 -column 3, line 11	1-8, 10-15
-/--		
<input checked="" type="checkbox"/> Further documents are listed in the continuation of box C. <input checked="" type="checkbox"/> Patent family members are listed in annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art. "A" document member of the same patent family		
Date of the actual completion of the international search  28 June 2000		Date of mailing of the international search report  06/07/2000
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016		Authorized officer  Westhues, T



## INTERNATIONAL SEARCH REPORT

Internat Application No

PCT/GB 00/00855

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 607 736 A (TEKNIKER) 27 July 1994 (1994-07-27) the whole document ---	8-14
A	EP 0 160 202 A (ENERGY CONVERSION DEVICES INC) 6 November 1985 (1985-11-06) the whole document ---	8-14
A	EP 0 795 622 A (MOTOROLA INC) 17 September 1997 (1997-09-17) column 4, line 33-53 ---	8,9
A	ANDERS S ET AL: "MECHANICAL PROPERTIES OF AMORPHOUS HARD CARBON FILMS PREPARED BY CATHODIC ARC DEPOSITION" MATERIALS RESEARCH SOCIETY SYMPOSIUM PROCEEDINGS, US, MATERIALS RESEARCH SOCIETY, PITTSBURG, PA, vol. 383, 17 April 1995 (1995-04-17), pages 453-458, XP000677135 ISSN: 0272-9172 ---	1-15
A	LIFSHITZ Y ET AL: "Optical and photoemission studies of DLC films prepared with a systematic variation of the sp:Spcomposition" DIAMOND AND RELATED MATERIALS, NL, ELSEVIER SCIENCE PUBLISHERS, AMSTERDAM, vol. 6, no. 5-7, 1 April 1997 (1997-04-01), pages 687-693, XP004081123 ISSN: 0925-9635 ---	8
A	FIELD J S ET AL: "The indentation characterisation of the mechanical properties of various carbon materials: glassy carbon, coke and pyrolytic graphite" CARBON, US, ELSEVIER SCIENCE PUBLISHING, NEW YORK, NY, vol. 34, no. 11, 1 January 1996 (1996-01-01), pages 1357-1366, XP004068901 ISSN: 0008-6223 the whole document --- -/--	8

## INTERNATIONAL SEARCH REPORT

Intern. Application No.  
PCT/GB 00/00855

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>CUOMO J J: "SPUTTER DEPOSITION OF DENSE DIAMOND-LIKE CARBON FILMS AT LOW TEMPERATURE" APPLIED PHYSICS LETTERS,US,AMERICAN INSTITUTE OF PHYSICS. NEW YORK, vol. 58, no. 5, 4 February 1991 (1991-02-04), pages 466-468, XP000206251 ISSN: 0003-6951 the whole document</p> <p>-----</p>	8

## INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/GB 00/00855

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
GB 2331998 A	09-06-1999	AU 1344399 A	16-06-1999
		WO 9927893 A	10-06-1999
EP 0480394 A	15-04-1992	JP 3013448 B	28-02-2000
		JP 4240007 A	27-08-1992
		JP 2557560 B	27-11-1996
		JP 4146007 A	20-05-1992
		JP 2867694 B	08-03-1999
		JP 4193406 A	13-07-1992
		DE 69107766 D	06-04-1995
		DE 69107766 T	29-06-1995
		KR 9504663 B	04-05-1995
		US 5178645 A	12-01-1993
		ZA 9108032 A	24-06-1992
EP 0796930 A	24-09-1997	DE 19610342 A	25-09-1997
US 5786038 A	28-07-1998	US 5616372 A	01-04-1997
EP 0607736 A	27-07-1994	ES 2060539 A	16-11-1994
EP 0160202 A	06-11-1985	AU 4184785 A	07-11-1985
		JP 60243275 A	03-12-1985
		PH 21325 A	28-09-1987
		ZA 8502298 A	27-11-1985
EP 0795622 A	17-09-1997	US 5837331 A	17-11-1998
		JP 9245626 A	19-09-1997

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